

# Fast Radiative Transfer with the Optimal Spectral Sampling (OSS) Technique

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## Overview

The Optimal Spectral Sampling (OSS) is a fast radiative transfer model that has been specifically designed for the modeling of radiances measured by infrared and microwave radiometers, but is applicable also through the visible and ultraviolet spectrum. OSS calculates the radiance averaged over a bandpass by calculating the monochromatic radiance at a small number (typically less than 4) of selected wavenumbers (nodes) within the bandpass and weighting the result. The nodes and weights are selected from a set of full line-by-line calculations on a number of reference profiles (the training set) which span the range of expected conditions. The selection process minimized the number of nodes for a required level of accuracy. Thus the OSS forward model reduces the number of monochromatic calculations per channel by as much as a factor of 2500, while still preserving Beer's Law.

The fact that OSS is fundamentally a monochromatic method provides the ability to accurately treat surface reflectance and spectral variations of the Planck function and surface emissivity within the channel passband. In addition, the method is readily coupled to multiple scattering calculations, an important factor for treating cloudy radiances. Among the advantages of the OSS method is that its numerical accuracy, with respect to a reference line-by-line model, is selectable, allowing the model to provide whatever balance of accuracy and computational speed is optimal for a particular application. This poster discusses the application of OSS to CLARREO and its utility in understanding the radiometric signature present in the output from climate model.

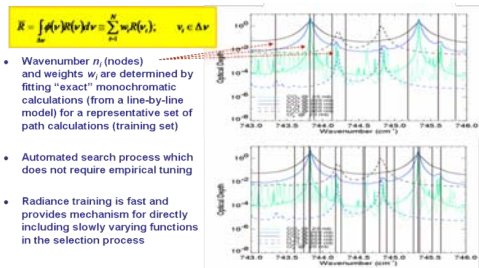
## Parameterization of Radiative Transfer Equation is Required for Many Applications

- Diverse remote sensing applications require radiative transfer algorithm speed, accuracy and flexibility
- Requirements for effective parameterization often conflict: high radiometric accuracy versus minimal computation time

- Available methods result in compromises:

- Model is geared toward a specific sensor or application
- Is not practical for use with changing observer altitude or model levels
- Does not obey Beer's law and thus not amenable to multiple scattering atmospheres
- Overall accuracy depends upon choice of predictors, generally determined by trial and error and depend specifically on the application (viewing geometry and spectral band), requiring re-training for alternate configurations
- Is not directly applicable to extended instrument functions such as sine

## Optimal Spectral Sampling (OSS) technique designed to provide rapid, accurate radiative transfer with physical consistency for all classes of remote sensing instrumentation

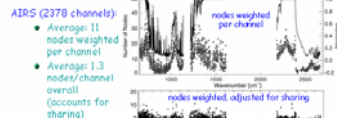


- Wavenumber  $n_i$  (nodes) and weights  $w_i$  are determined by fitting "exact" monochromatic calculations (from a line-by-line model) for a representative set of path calculations (training set)
- Automated search process which does not require empirical tuning
- Radiance training is fast and provides mechanism for directly including slowly varying functions in the selection process

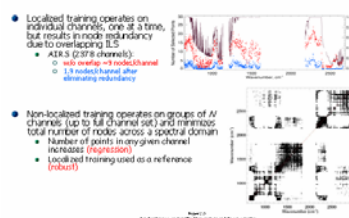
## Automated Training Process to Determine Nodes and Weights

### Training Approaches: 1) Local Training

- Operates on individual channels, one at a time
- Nodes for each channel required to be within spectral range of channel response
- Nodes may be shared between channels with overlapping responses



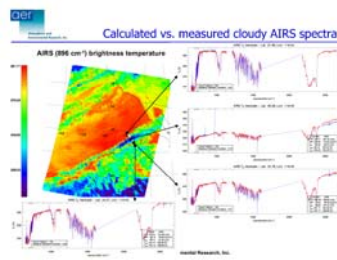
### Non-localized training used to reduce overall number of selected nodes



### Training Approaches: 2) Global Training

- Operates on groups of channels (up to the full channel set) simultaneously
- Uses clustering of monochromatic radiances to efficiently account for spectral correlations
  - Condenses the information of the full channel set into a minimal number of nodes
- Monochromatic RT at a relatively few nodes determines radiances for full channel set
- Optionally, can be fit to channel subset, or first  $K$  principal components of channel set, or radiances filtered by PC transformation
  - Reduces information relative to full channel set

## Extensive/Independent Validation on a Variety of Data



### Application to IASI

Global and local training results

WV band	Spectral range (cm <sup>-1</sup> )	Number of channels	Local	Global	Global/Local
1	640-1100	1100	1100	220	0.20
2	1100-1400	1100	1100	220	0.20
3	1400-1700	1100	1100	220	0.20
Total		3300	3300	660	0.20

- Training conditions:
- IASI accuracy requirement
  - 13 variable gases: H<sub>2</sub>O, O<sub>3</sub>, CO<sub>2</sub>, CO, CH<sub>4</sub>, H<sub>2</sub>O, HNO<sub>2</sub>, SO<sub>2</sub>, OCS, OF<sub>2</sub>
  - 5 fixed gases: O<sub>2</sub>, NO<sub>2</sub>, NH<sub>3</sub>, N<sub>2</sub>
  - Sources: ECMWF for H<sub>2</sub>O, O<sub>3</sub>, CO<sub>2</sub>, CO, CH<sub>4</sub>, H<sub>2</sub>O, HNO<sub>2</sub>, SO<sub>2</sub>, OCS, OF<sub>2</sub>, F11, F12, CF<sub>4</sub>, HFC, HFO, PFC, SF<sub>6</sub>, NF<sub>3</sub>, C<sub>2</sub>F<sub>6</sub>, C<sub>3</sub>F<sub>8</sub>, C<sub>4</sub>F<sub>10</sub>, C<sub>5</sub>F<sub>12</sub>, C<sub>6</sub>F<sub>14</sub>, C<sub>7</sub>F<sub>16</sub>, C<sub>8</sub>F<sub>18</sub>, C<sub>9</sub>F<sub>20</sub>, C<sub>10</sub>F<sub>22</sub>, C<sub>11</sub>F<sub>24</sub>, C<sub>12</sub>F<sub>26</sub>, C<sub>13</sub>F<sub>28</sub>, C<sub>14</sub>F<sub>30</sub>, C<sub>15</sub>F<sub>32</sub>, C<sub>16</sub>F<sub>34</sub>, C<sub>17</sub>F<sub>36</sub>, C<sub>18</sub>F<sub>38</sub>, C<sub>19</sub>F<sub>40</sub>, C<sub>20</sub>F<sub>42</sub>, C<sub>21</sub>F<sub>44</sub>, C<sub>22</sub>F<sub>46</sub>, C<sub>23</sub>F<sub>48</sub>, C<sub>24</sub>F<sub>50</sub>, C<sub>25</sub>F<sub>52</sub>, C<sub>26</sub>F<sub>54</sub>, 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## Scattering Forward Model

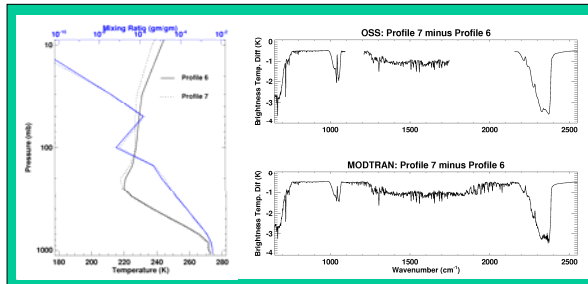
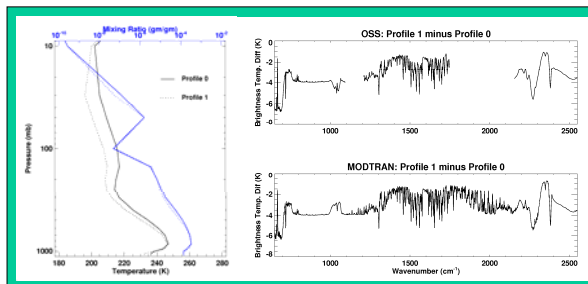
- OSSSCAT is single-wavelength version of CHARTS adding-doubling RTM
  - Uses same molecular absorption and weighted monochromatic radiances as non-scattering RTM
- Cloud module converts from physical properties (e.g., IWP, LWP,  $D_{eff}$ , top, thickness,  $T(p)$ ) to optical properties (absorption and scattering optical depths, asymmetry parameter)
  - Look-up table
    - Size distributions based on in-situ aircraft measurements
    - File for liquid
    - MAIA for ice - with temperature-dependent shape recipes
- Optical properties linearly interpolated from hinge points to OSS nodes

## OSS Forward Model

- RTM structure
  - Main loop is the node loop
  - Internal channel loop to update channel radiance and Jacobians
  - Similar structure adopted for CRTM
- LUT of  $k$  and  $Q$  for all relevant molecules as a function of temperature
  - Self broadening included for water vapor
  - Maximum brightness temperature error with current LUT: 0.05K in infrared and ~0.03K in microwave
- Use simple monochromatic RT model (clear or scattering)
  - Jacobians (required for retrieval applications) are straightforward in the clear-sky (e.g. CRTM ATBD)



Brightness Temperature Differences Between Profiles Illustrate the Radiometric Impact of Changing Temperature and Water Vapor Profiles: OSS and MODTRAN Exhibit Similar Sensitivity



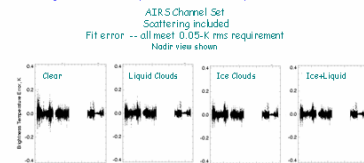
## Multiple Scattering

### Multiple Scattering Acceleration

- With scattering, execution time is dominated by radiative transfer integration
  - Contrasts with non-scattering, where band transmittance calculation may be a bigger factor
  - OSS RT timing ~proportional to number of nodes
  - TPTR RT timing ~proportional to number of channels
  - OSS is faster than TPTR methods only when the number of nodes / number of channels < 1
- Scattering calculations do not have to be performed for every OSS node
  - Scattering correction may be predicted based on a few nodes only
 
$$\tilde{R} = \sum_i w_i R^{sc}(v_i) + \sum_j C_j [R(v_j) - R^{sc}(v_j)]$$
    - $\tilde{R}$  is radiance from scattering model
    - $R^{sc}$  is radiance from non-scattering model
    - $w_i$  are the ordinary OSS weights
    - $C_j$  are a subset of the set of the OSS nodes ( $S$ ) for the channel
    - $C_j$  are regression coefficients
- Number of predictors can be tuned to control balance between cloudy radiance accuracy and computation speed
  - Some relaxation of accuracy may be tolerable in clouds with high optical depth, in proportion to uncertainties in optical properties

### Cloudy and Clear Fit

- OSS selection requires accuracy threshold be met for each training set individually and simultaneously



## Scattering Prediction Performance for MODIS

MODIS Channel #	Bandpass (nm)	Number of nodes*	Number of predictor nodes*
10	3660 - 3680	10	4
11	3250 - 3280	9	1
22	3250 - 3280	9	2
24	4430 - 4480	10	2
26	4480 - 4540	10	2
27	6300 - 6350	14	1
28	7200 - 7250	18	2
29	8400 - 8500	14	3
31	10700 - 11200	4	1
32	11700 - 12200	4	1
33	15100 - 15400	10	1
34	13400 - 13700	21	1
35	13700 - 14000	24	1
36	14000 - 14300	21	1
Average		13.6	1.7

Wide-band channels, such as with MODIS are more challenging than narrow-band channels for OSS scattering efficiency, since there are more nodes/channel

Selected IR channels

Localized training used  
Generalized may require fewer predictors

\* For error threshold 0.05K, clear and cloudy training  
\* For scattering prediction error threshold 0.1K

## Application to CLARREO

### OSS Incorporated into SIMRAD Infrastructure

- SIMRAD developed by Stephen Leroy (Harvard) to run MODTRAN for multiple input atmospheres from climate models
- OSS module under development to improve radiative transfer timing and overall accuracy
  - Remove Jacobian calculations
- Prototype calculations conducted using nominal 3-band FTS
  - Will be expanded to full CLARREO waveband
- Scattering module under development
  - Additional timing enhancements will be required to reach CLARREO computation goals

## EUMETSAT Comparison of OSS and RT-IASI

Timing Results (in sec/profile)		
	Direct only	Direct + Jacobians
RTIASI	1.11	11.42
OSS	-	0.67

Averaged over 5300 profiles, on IBM power 2: x1f90 -03 -q64

Nov 10  
Advanced High Resolution Infrared Observations  
Contract, January 17-17 April 2010

EUMETSAT

OSS is 3.8x Faster than MODTRAN for Clear-Sky; Cloudy-Sky Anticipated to Meet CLARREO Simulation Requirement of Less Than 1 Second per Profile

Model	Time (sec)	Spectral Elements	Profiles	Time per Profile per Spectral Element
MODTRAN	228.0	1900	600	2.0e-4
OSS	40.6	1305	600	5.2e-5

We would like to acknowledge others that contributed to this poster:  
Bob d'Entremont, Karen Cady-Pereira, Richard Lynch (AER); Jim Anderson, Stephen Leroy (Harvard); Stephen Tjennes (EUMETSAT)